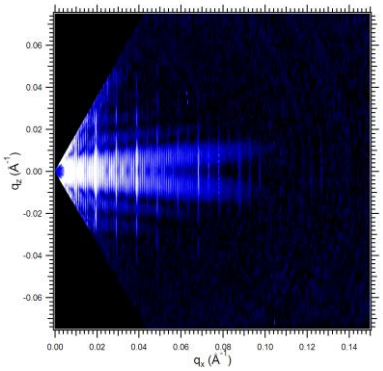
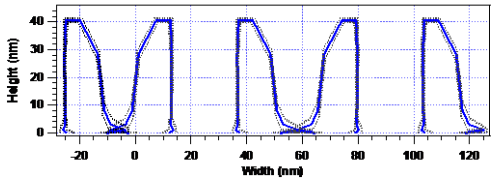








Compact X-ray Sources and Applications for Semiconductor Metrology

R. Joseph Kline

NIST
National Institute of Standards and Technology
Technology Administration
U.S. Department of Commerce

Contributors

NIST

- Adam Hannon*
- Christopher Liman*
- Daniel Sunday
- William Thompson (*Lam Research*)
- Donald Windover
- *Wen-li Wu (retired)*

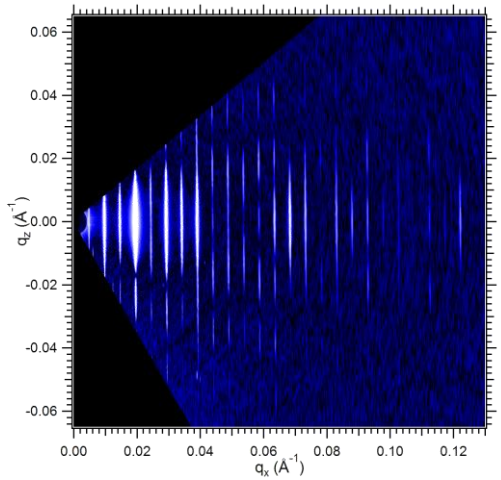
Intel Corporation

- Jasmeet Chawla
- Scott List

APS – DND-CAT

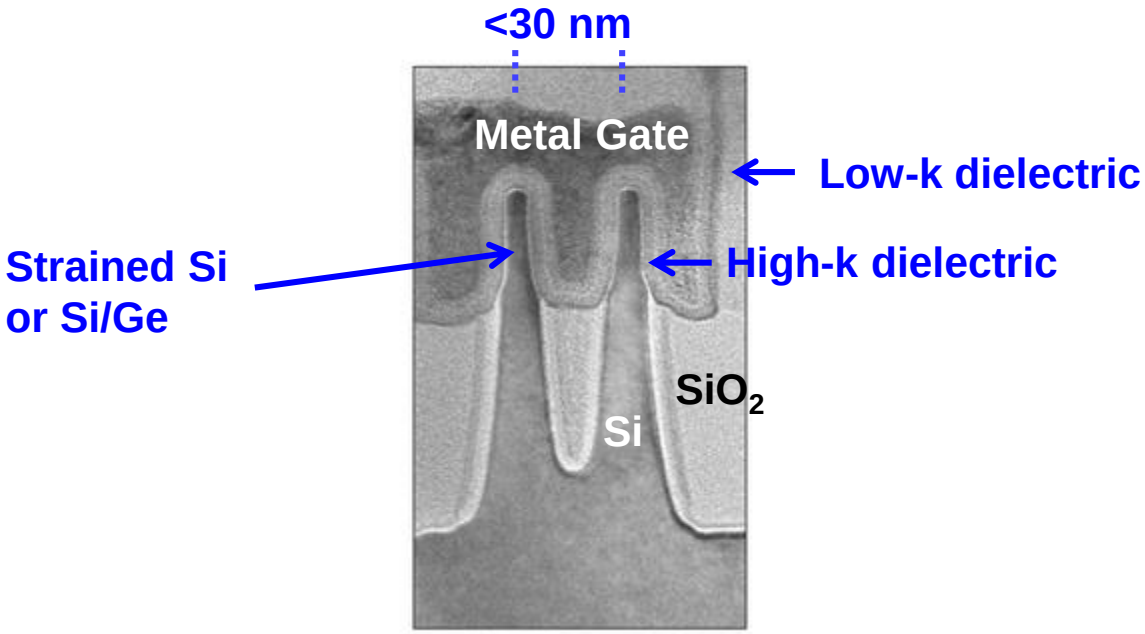
- Denis T. Keane
- Steven J. Weigand





***NIST National Research Council Postdoctoral Fellowship**
2 year, $70k/year stipend to work at NIST, requires US citizenship
Contact me at Joe.Kline@nist.gov for more info

X-ray Metrology Based Solutions

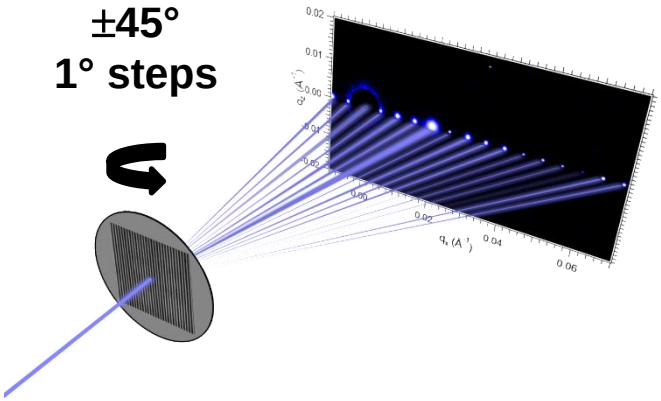


Intel.com

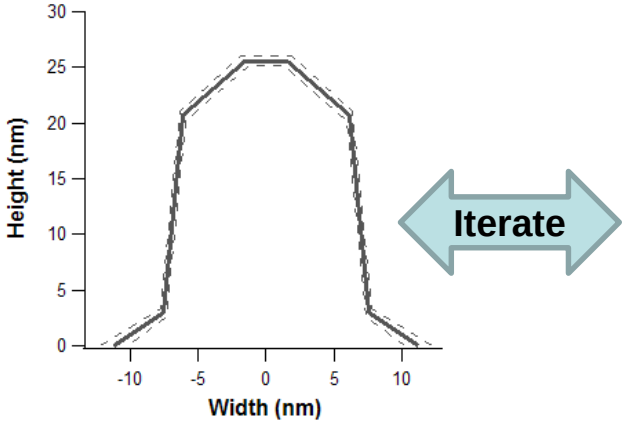
- Shape metrology – small angle X-ray scattering (CDSAXS)
- Strain in SiGe and III-V multilayers – high-resolution XRD
- Film thickness and density – X-ray reflectivity
- Surface composition and chemistry – XPS
- Film bulk composition – micro-XRF and XRD
- Chip and packaging imaging – X-ray tomography
- Composition and bonding – NEXAFS and EXAFS

Critical-Dimension Small Angle X-ray Scattering

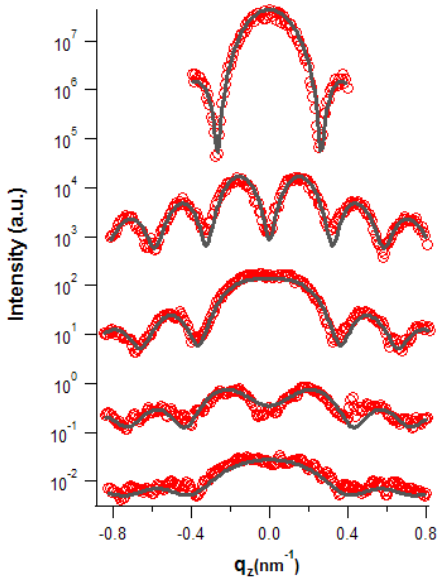
±45°
1° steps



Inverse Fitting



Compare guess to data



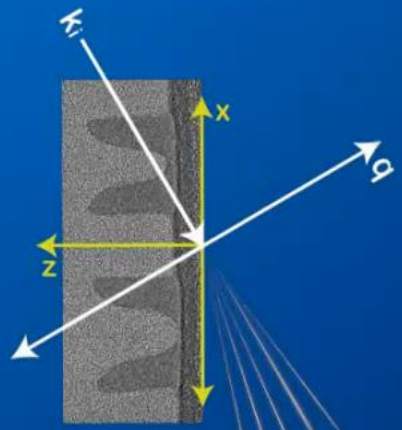
$$I(\boldsymbol{Q}) = |F(\boldsymbol{Q})|^2 e^{-\boldsymbol{Q}^2 DW^2}$$

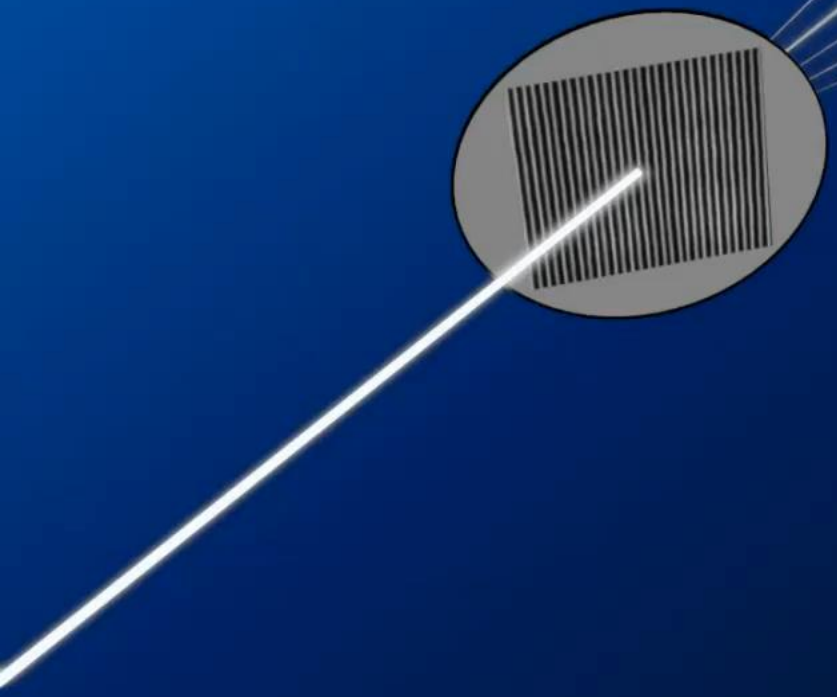
Variable-angle transmission SAXS:

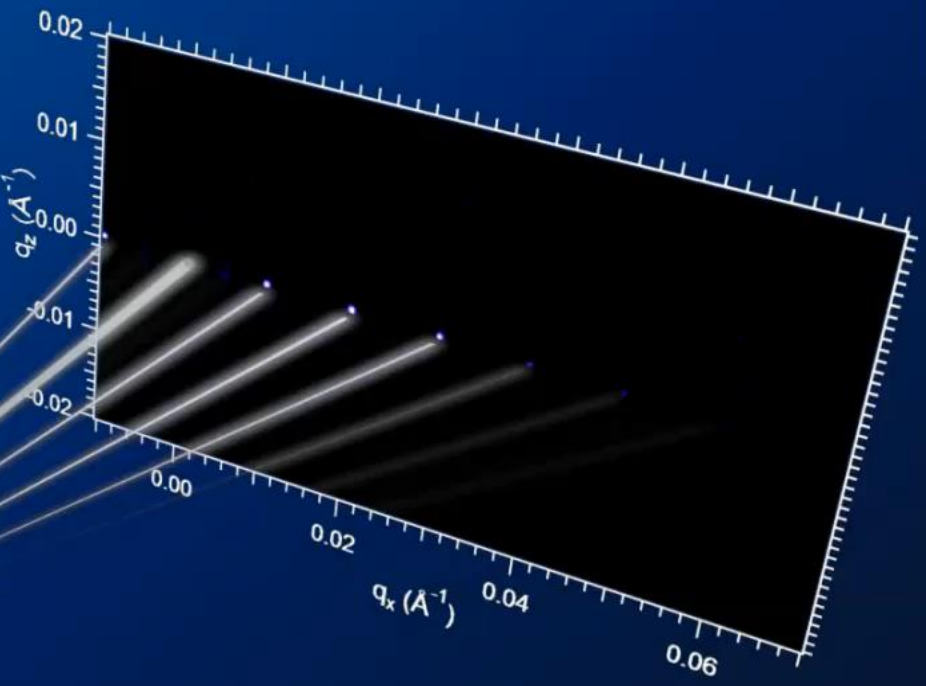
- Developed for in-line process control in semiconductor industry on small targets
- “Single crystal” diffraction with nanopattern as lattice, pattern shape as atom
- Hard X-rays (>15 keV) for transmission through wafer (also use soft)
- Measure 1D, 2D, or 3D periodic nanopatterns
- Diffraction pattern is Fourier transform of electron density distribution
- Use inverse, iterative method to calculate simulated pattern from trial solution
- Result is the average shape of the repeated nanostructure

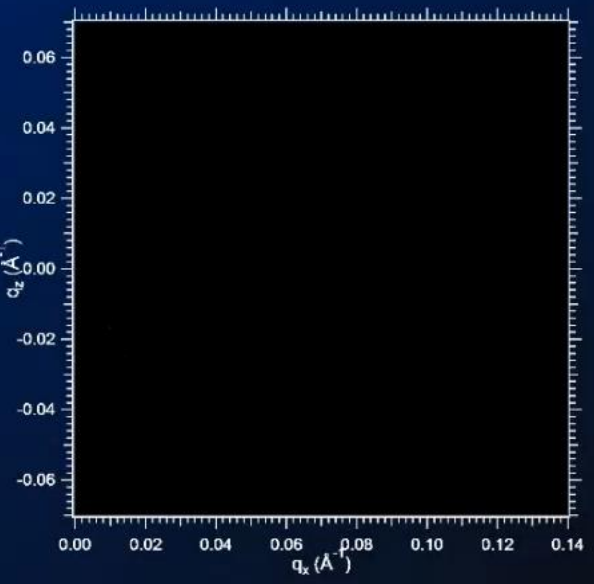
D.F. Sunday et al, *J. Appl. Cryst.* 48, 2015

CDSAXS Measurement



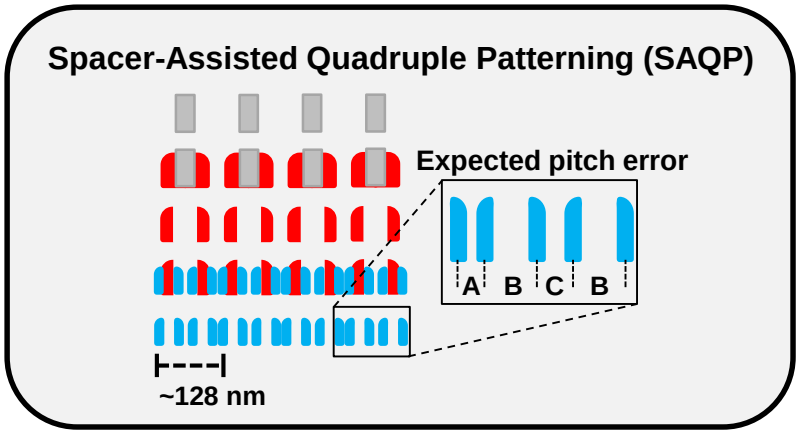


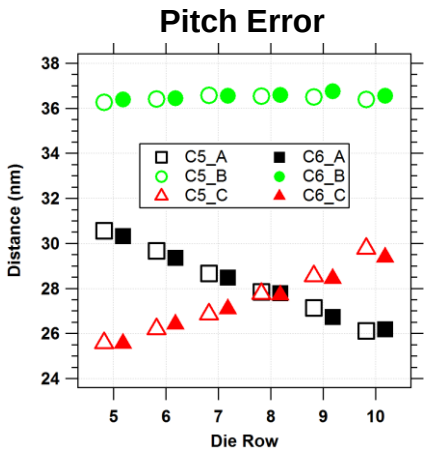


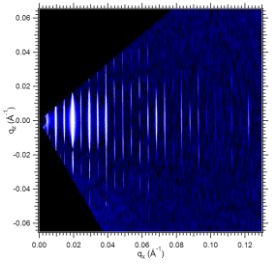


*Scattering angle exaggerated for clarity

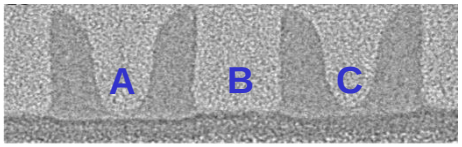
CD-SAXS Measurement of SAQP Pitch Error

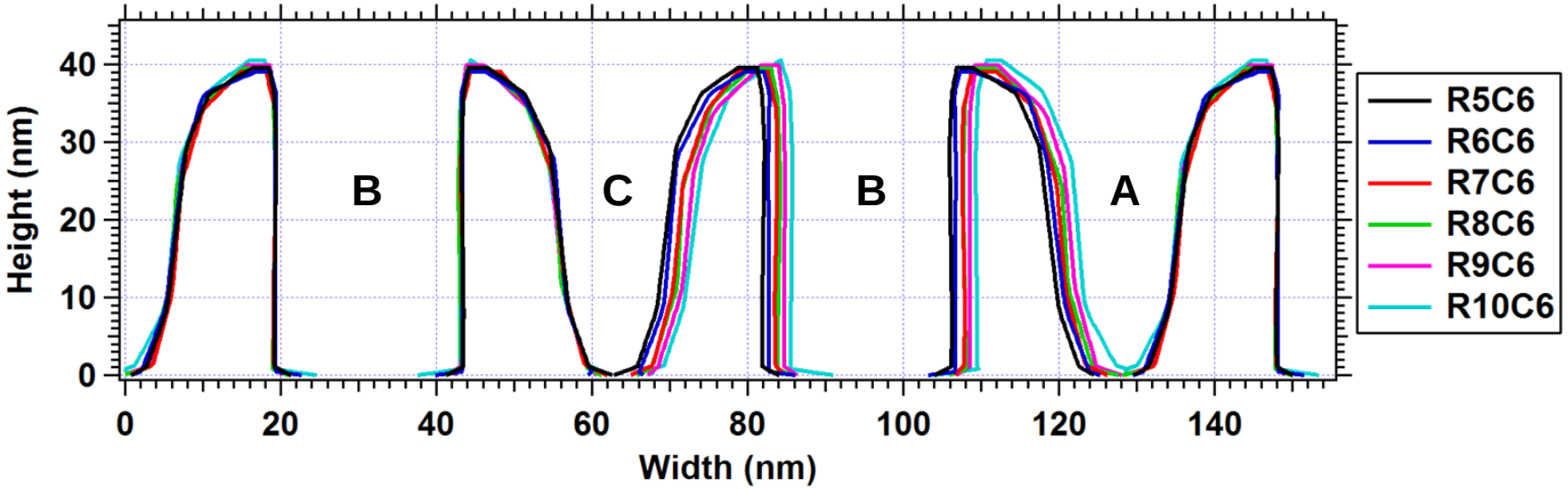






XTEM





- CD-SAXS resolves sub-nm changes in the pitch offset (matches xTEM)
- Samples had similar line shape with primary difference being shift

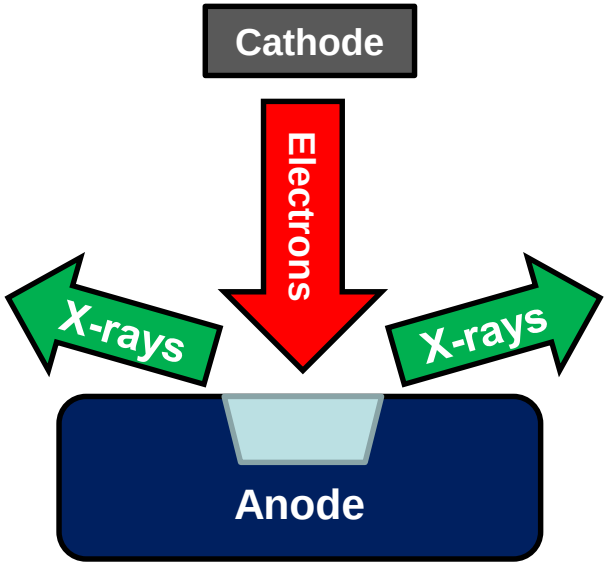
D.F. Sunday et al, *J. Appl. Cryst.* 48, 2015

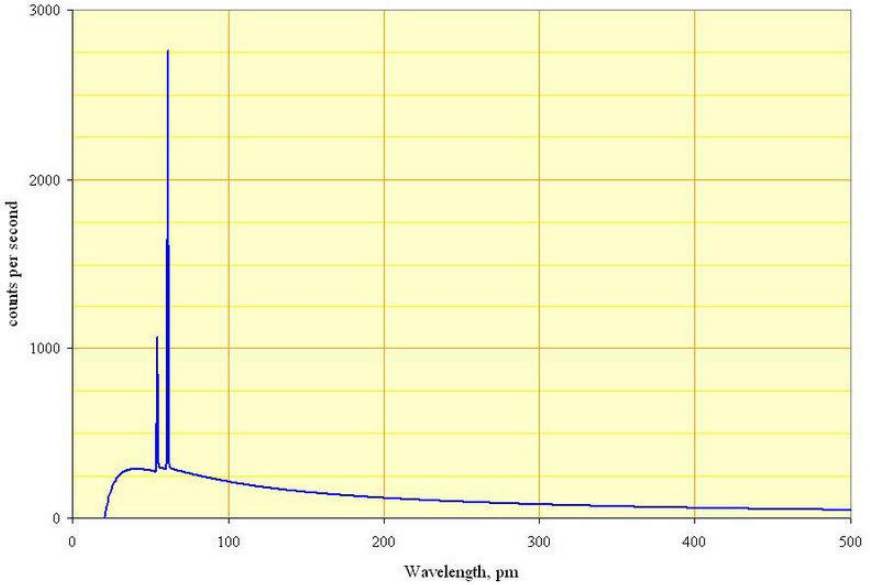
X-ray Source Requirements by Application

Measurement	Energy	Bandwidth	Divergence	Spot Size	Tunable E
CDSAXS	>20 keV	<1%*	~0.5 mrad	<100 μm	No
Imaging	50-200 keV	-	-	<<1 μm	No
XRD	8-20 keV	<0.1%	1 mrad	<50 μm	No
HR-XRD	8-10 keV	<0.01%	<0.2 mrad	<50 μm	No
XRR/GIXRD	5-10 keV	<0.01%	<0.2 mrad	<50 μm	No
μ-XRF	>5 keV	-	-	<50 μm	No
LE-XRF	1-2 keV	-	-	<50 μm	No
XPS	1-2 keV	<0.2 eV	-	<50 μm	No
NEXAFS	<1 keV	0.1 eV	-	<50 μm	Yes
EXAFS	3-20 keV	<0.1%	-	<50 μm	Yes

- Key requirements are fast and small spot
- 10-20x flux increase would be huge for currently used measurements
- Others require 100-1000x flux increase of rotating anode to become practical
- Ideally solution in <2 years

X-ray Sources – Electron Impact

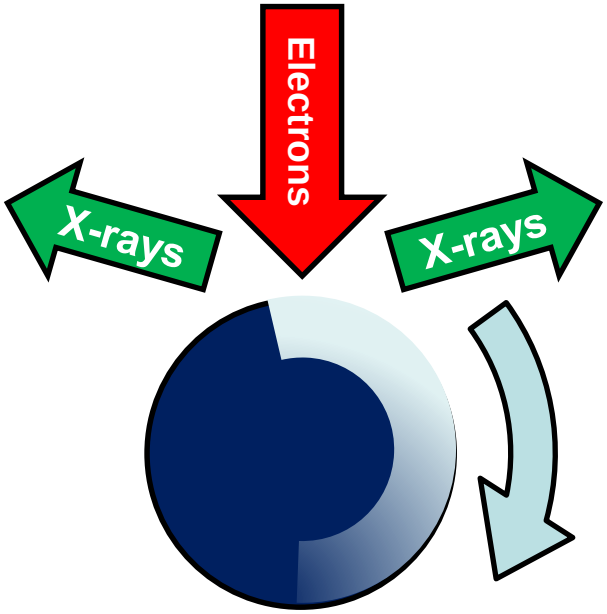




Wikipedia

- Classic X-ray tube
- Characteristic X-ray emission with Bremsstrahlung background
 - Limited to available target materials
 - Continuous emission up to accelerating voltage
- Power density limited by thermal anode damage
 - Rate of heat dissipation
 - Location of energy deposition

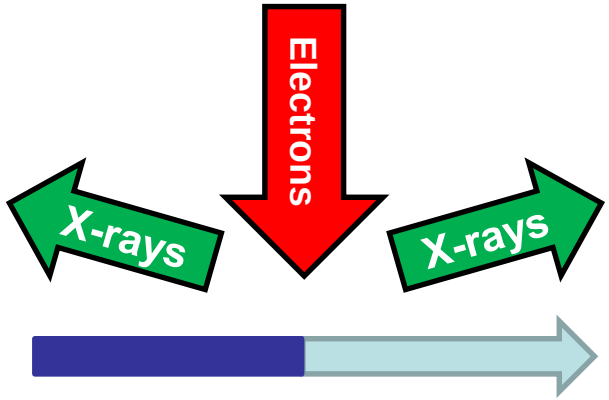
Electron Impact Source – Beyond X-ray Tube





- Classic method - rotating anode
 - Larger circumference and faster rotation allow higher power density
 - Commercial systems up to 12000 RPM, 28 cm diameter
 - Microfocus limited by wobble at larger diameters/RPM

Electron Impact Source – Metal Jet Anode

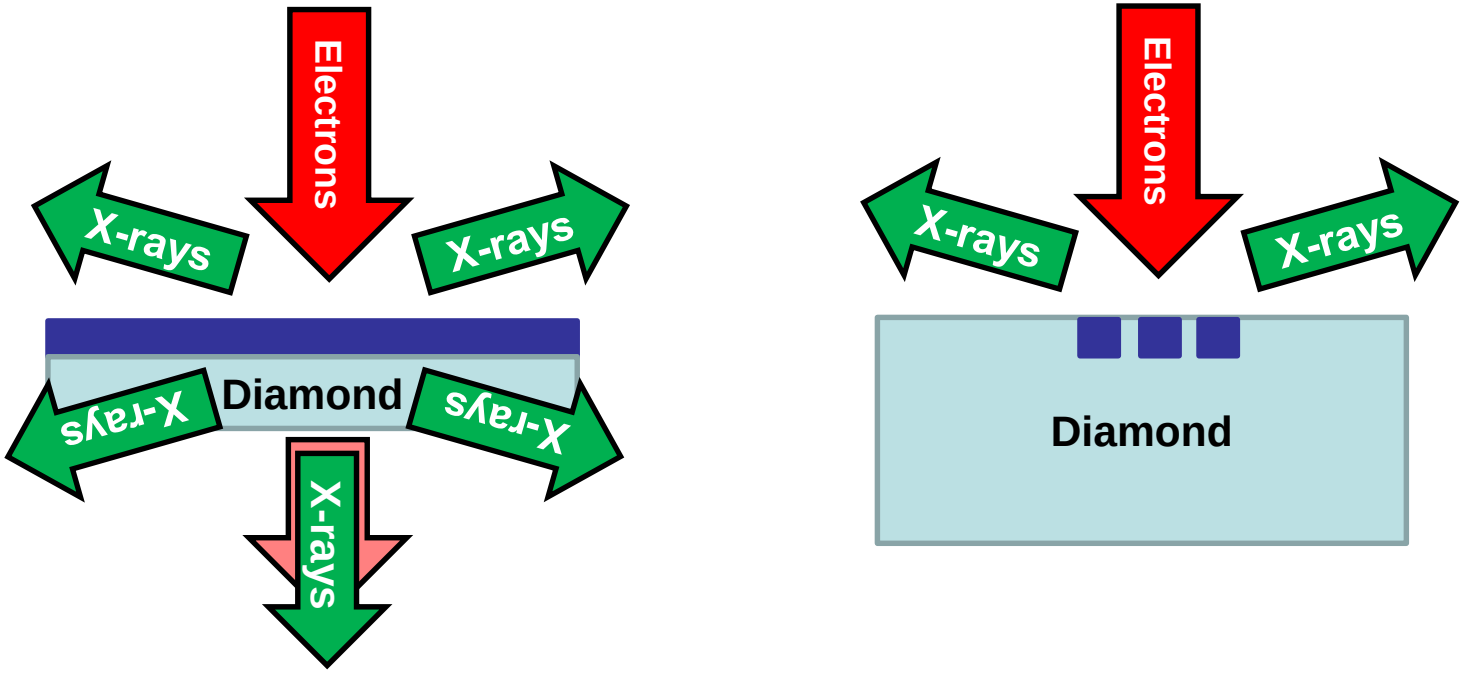


High flow metal jet



- Replace rotating anode with metal jet
 - Constantly recreate the source
 - Mass flow transports heat
 - Limited to certain alloys that are liquid at low temperatures
 - Must keep secondary ions out of electron gun

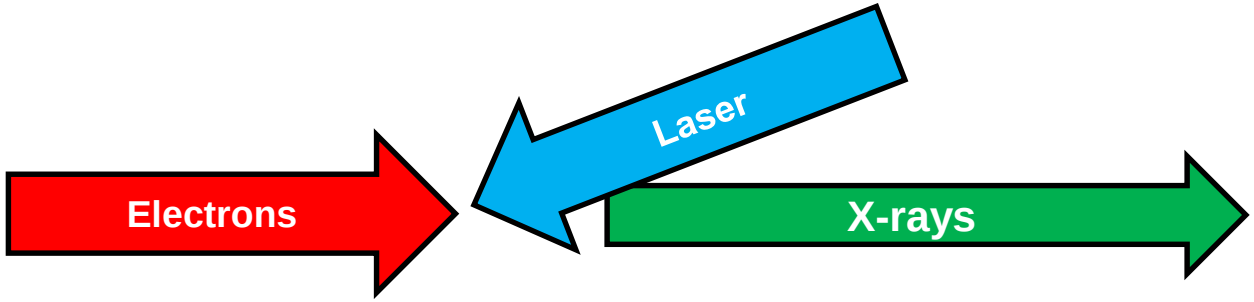
Electron Impact Source – Heat Management Substrate



- Increase thermal conductivity of substrate and control where electron dose is absorbed
 - Diamond has high thermal conductivity and low electron/X-ray absorption
 - Thin anode means electrons only absorbed where X-rays escape
 - Mechanical and chemical stability of metal-diamond interface

Inverse Compton Scattering

$$\lambda_X = \lambda_L \frac{1 + \gamma^2\theta^2}{4\gamma^2}$$

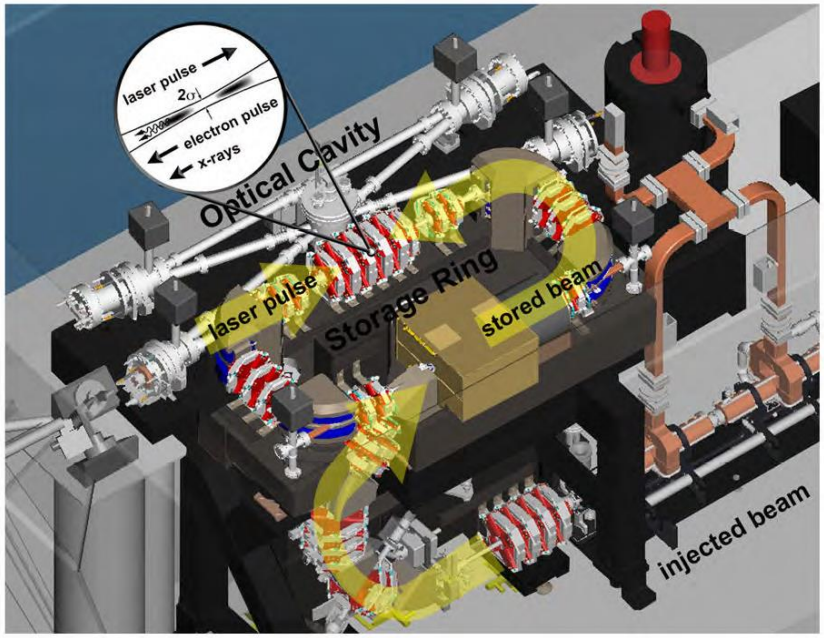


$$N_\gamma \approx \frac{4x10^3\, N_e U_L(J)}{Z_R(\mu m)}$$

- Inverse Compton scattering involves the interaction of relativistic electrons with photons
- X-rays emit in narrow cone with a few percent bandwidth
- Electron energy and laser frequency determine X-ray energy
 - Works up to gamma rays
- X-ray flux determined by e-beam current, laser intensity and interaction volume

G. Krafft, Rev. Acc. Sci. Tech., 3, 2010, 147

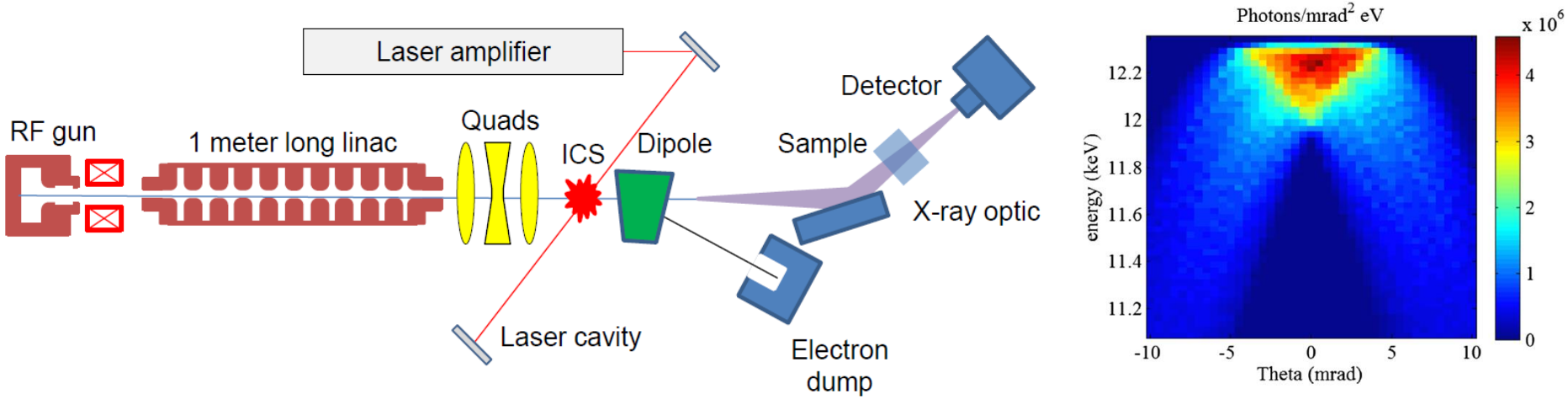
Synchrotron-based ICS



Abendroth et al, **J Struct Funct Genomics** 11, 2010, 91

- LINAC accelerates electrons to ~30 MeV and stores electron beam in storage ring
- Laser cavity allows large stored optical power
- Each electron bunch creates many X-ray pulses
- Bending magnets are not efficient at compressing electron beam

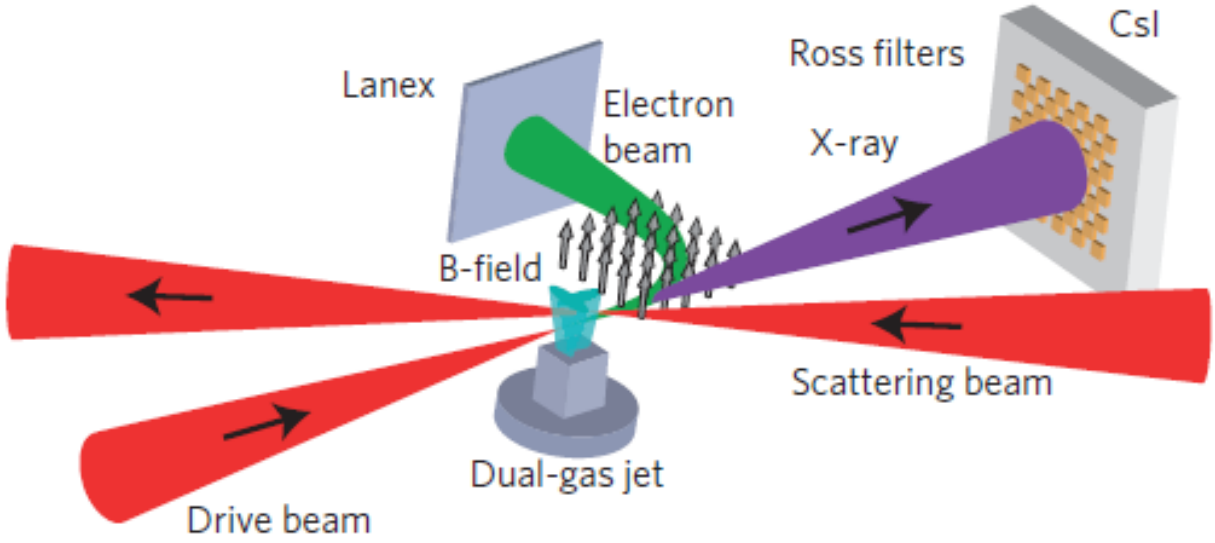
LINAC-based ICS



Graves et al, . ***Phys. Rev. Spec. Top. - Accel. Beams, 17,*** 2014

- LINAC accelerates electrons to ~20 MeV and each bunch collides with laser pulse
- LINAC more tightly focuses electron bunch than bending magnets
- Collide micron-sized electron bunch with micro-sized laser pulse
- Multiple groups making LINAC-based ICS sources

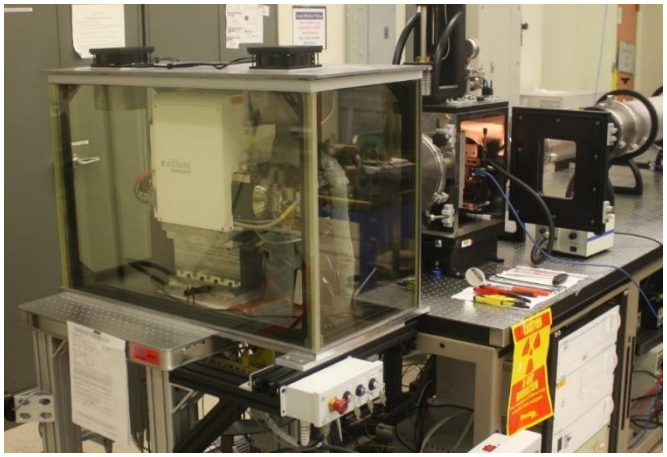
Laser-wakefield ICS

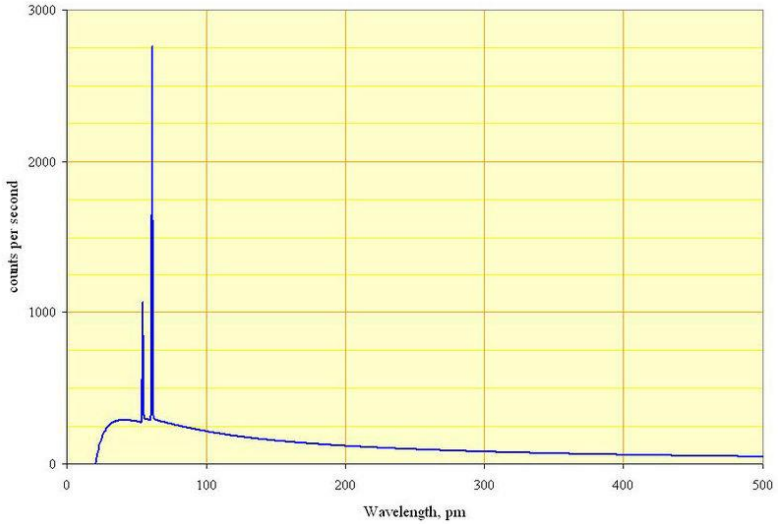


Powers et al, ***Nature Photonics*** *8, 2014*

- Use laser to create MeV electron beam from collision with gas jet and laser-wakefield acceleration of electrons in the plasma
 - No LINAC
- Second laser hits electron beam to create X-rays
- Interaction footprint is small, although current lasers are very large

Radiation Produced by X-ray Sources

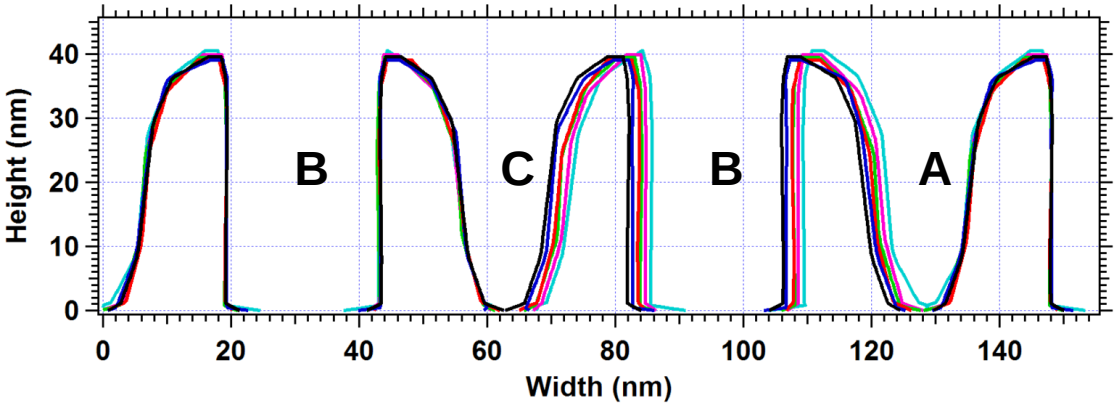


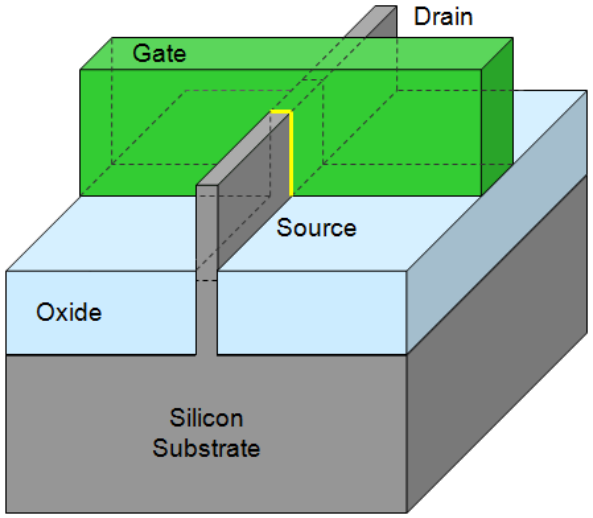


Wikipedia

- Electron impact sources
 - Characteristic X-rays (5-60 keV)
 - Bremsstrahlung X-rays (up to accelerating voltage, 50-300 keV)
- Accelerator sources
 - Main X-ray beam (10-30 keV)
 - Bremsstrahlung X-rays (up to accelerating voltage)
 - 20-40 MeV (Gamma rays)
 - Secondary neutrons (photonuclear effect)

X-ray Metrology for the Semiconductor Industry





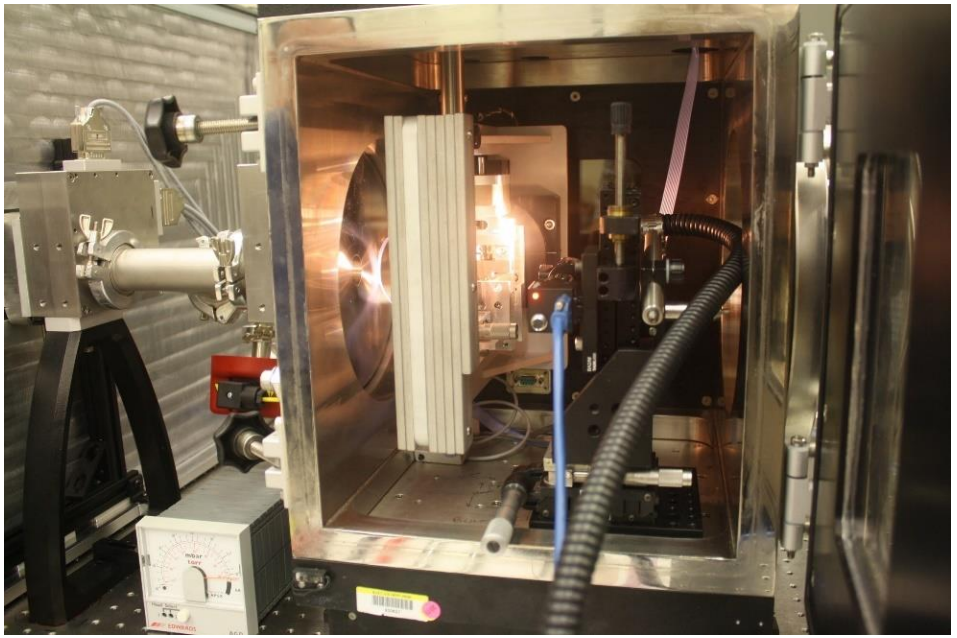
finFET (Intel.com)

- X-rays have potential to solve critical metrology challenges to semiconductor industry
- New X-ray sources with much increased flux would enable a number of game changing new measurements
- A number of new source technologies are under development with potential to substantially enhance the current source capability

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CDSAXS Short Course at NIST, August 2016





- Hosted 25 scientists from semiconductor industry for 2 day short course
 - Attendance included semiconductor companies, most metrology instrument manufacturers and X-ray component manufacturers
- Covered theory of CDSAXS including scattering and instrumentation
- Hands-on demonstrations of NIST data fitting and collection on our instrument
- Contact joe.kline@nist.gov for more information